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Spherical Arrays for Wireless Channel Characterization and Emulation

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Abstract — **Three types of spherical arrays for use in wireless communication research are presented. First, a spherical array of 32 monopoles with beam steering in arbitrary direction and with arbitrary polarization is described. Next, a spherical array with 16 quad-ridged open-flared horns is introduced, offering better wideband performance and easier beam steering. Finally, a multi-probe setup for over-the-air testing of multiple-input multiple-output mobile devices is presented, being essentially a spherical array with inward radiation.**

1 INTRODUCTION

All the recent standards for mobile communication count on multipath propagation of radio waves as an important means of increasing the data throughput when the time and frequency resources are saturated. In order to evaluate the true potential of the multipath propagation, measurements of the propagation channel characteristics in typical environments (buildings, street canyons, etc.) are needed. As the directions of arrival of the electromagnetic wave to the mobile device can have generally arbitrary angle, an (ideal) antenna array for use in the channel measurement should be fully steerable over the full hemisphere, with reasonably small beamwidth to differentiate between wave clusters. These requirements, in addition to a good mobility, are satisfied by spherical arrays.

Spherical arrays with various array elements and for various kinds of applications have been reported in literature. Rectangular patches are used in [1, 2], whereas circular patches are utilized in [3]. Other types of array elements include crossed dipoles [4, 5], spiral antennas presented in [6], and finally [7] describes a spherical array with annular ring antennas as elements. Distribution of the elements across the surface of the sphere is discussed in [8, 9].

In this paper, we present two designs of spherical arrays with broadband to ultrawideband performance, a *spherical array of monopoles* and a *spherical horn array*. Both have been used in channel measurement campaigns in the APNet group at Aalborg University (AAU), focused at obtaining channel information for indoor office environments and building concourses, and also for outdoor scenarios in urban conditions, with many reflected and diffracted rays to be detected [10, 11].

In addition, another type of spherical array in use at AAU is introduced: a *spherical over-the-air* (OTA) *testing range* with inward radiation, for propagation channel emulation, as opposed to its analysis. This structure is built in an anechoic chamber and its purpose is to test real-life performance of mobile devices under multipath conditions. The radiation properties of this array are characterized by homogeneity of the field at the sphere center, rather than its radiation pattern.

The paper is organized as follows. The spherical array of monopoles is described in Section 2, with radiation patterns of a single element and of the entire array with beamforming. The spherical horn array is then reported in Section 3, showing gain of a single horn and an example of the sum beam of the entire array. The spherical OTA range is shortly introduced in Section 4, and Section 5 concludes the paper.

2 SPHERICAL MONOPOLE ARRAY

The first design of a spherical array was intended for operation in frequency band 3–6 GHz. The array consists of a brass sphere with diameter of 195 mm, mounted on a metallic rod, with 32 monopoles distributed evenly over the sphere surface (Fig. 1). The monopoles are simply the backsides of SMA connectors, 17.9 mm long stubs with teflon coating. The array has been designed with the help of the finite-difference time-domain method in spherical coordinates—more details about the array and the simulation method are given in [12].

The array is capable of transmitting and receiving in arbitrary direction and with arbitrary polarization, although steering of the beam required special processing due to perpendicular radiation of the array elements. An example of radiation pattern of a single monopole when all other are terminated with 50 Ω loads is presented in Fig. 2. Total gain of the monopole is plotted in the entire hemisphere with θ and ϕ being the spherical coordinates of the direction of radiation.

The fact that a single element has its radiation

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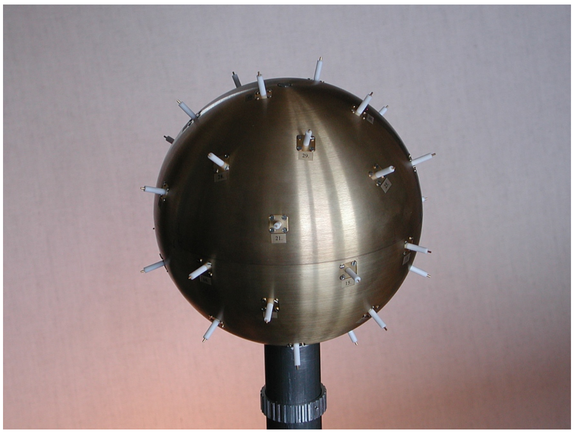

Figure 1: Spherical array of monopoles.

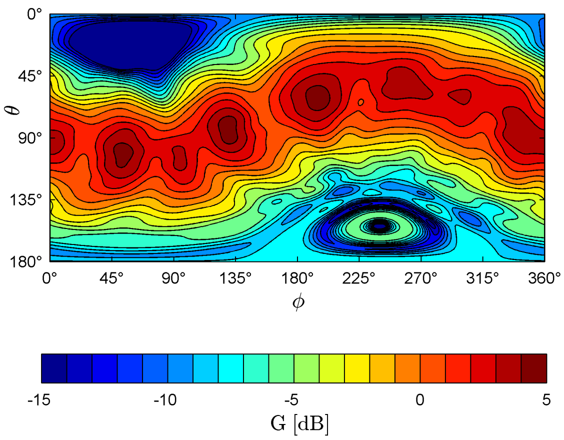

Figure 2: Total gain of monopole no. 31 positioned near the top of the sphere (simulated).

pattern distributed in a band across the hemisphere makes the beamforming a difficult task. Fig. 3 shows the total E-field radiation pattern in vertical (θ) polarization, with the beam steered into $\theta = 80°$, $\phi = 70°$ direction, for which the feeding of the monopoles was optimized to give the highest possible suppression of sidelobes. It is clear that the suppression is not ideal since the sidelobe level reaches -6 dB. This figure might be improved by increasing the number of monopoles in the array, however this would not only require more processing hardware (channel sounder inputs) but also increase the mutual coupling between the monopoles, which, in the current version, is below -18 dB.

3 SPHERICAL HORN ARRAY

In order to avoid the extra processing related to beam steering, another design of spherical array has been realized at AAU: spherical horn array

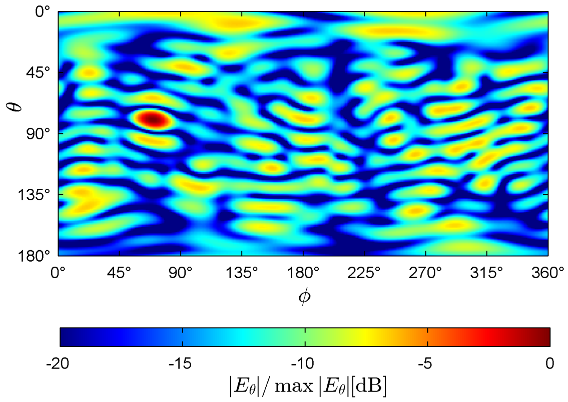

Figure 3: E-field radiation pattern with beam steered to $\theta = 80°$, $\phi = 70°$ direction.

for frequency range 0.6–6 GHz [13]. The elements of this array are 16 dual-polarized quad-ridged horns with diamond-shaped waveguide section and an open flare, mounted over a sphere in a quasi-homogeneous pattern covering theta angles up to 110 degrees (see Fig. 4).

Figure 4: Spherical array of dual-polarized open-flared ridged horn antennas.

The gain of the horn grows with frequency and reaches 12 dBi near the upper end of the band. On the other hand, the beam becomes narrower with frequency, with full-width half-maximum beamwidth of $40°$ at 6 GHz (Fig. 6). These data include the influence of the neighboring antennas in the array.

The design of the horn antenna has been optimized with help of simulations to have lowest possible reflection coefficient in the entire frequency range, resulting in $s_{11} = -10$ dB in most of the range, with some parts having -6 dB. The radiation properties were largely insensitive to small changes in geometry.

Figure 5: Dual-polarized open-flared ridged horn antenna used as the array element.

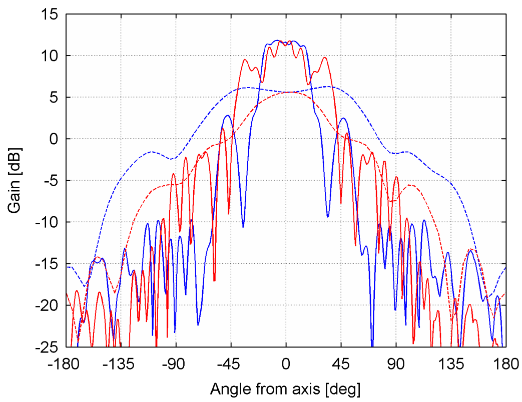

Figure 6: Gain of the top horn; solid line 6 GHz, dashed line 776 MHz; E-plane in red, H-plane in blue.

The horns are arranged in 4 groups achieving quasi-homogeneous coverage with emphasis on the upper hemisphere. The lower hemisphere is not completely covered as the probability of a signal incoming from the ground is quite low. The distribution has been optimized to minimize coupling between the elements. Typical values of mutual coupling (s_{21}) between the array elements are lower than -25 dB, with the worst case being -19 dB at the lower end of the frequency range.

Homogeneity of the array in retrieving the directional channel information over all directions is described by the sum beam of the array, which is obtained by summing power contributions from all of the antennas in the array, for each polarization. The sum beam is homogeneous over the upper hemisphere within 3 dB at the lower end and 6 dB at the upper end of the band. An example for horizontal (ϕ) polarization at 6 GHz is shown in Fig. 7. The center of the plot corresponds to the upward direction of radiation, while the circumference corresponds to the downward direction, with the radius linearly proportional to the theta angle.

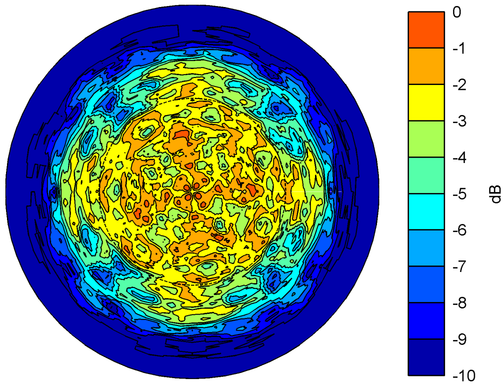

Figure 7: Sum beam of the horn array at 6 GHz, ϕ polarization.

4 OTA TESTING RANGE

A fundamentally different spherical array has recently been built at AAU—an inward radiating OTA range for testing multiple-input multiple-output (MIMO) mobile devices. It uses the same type of elements (quad-ridged open-flared horns) as in the previous array, but this time arranged around a circumference of a ring (subset of a sphere), creating multipath propagation environment for the device placed at its center (see Fig. 8). Details of generating a plane wave with this setup have been described in [14].

Although the current installation allows for generating incoming waves from the horizon only, a full 3D spherical configuration that will enable waves from arbitrary direction is in development [15].

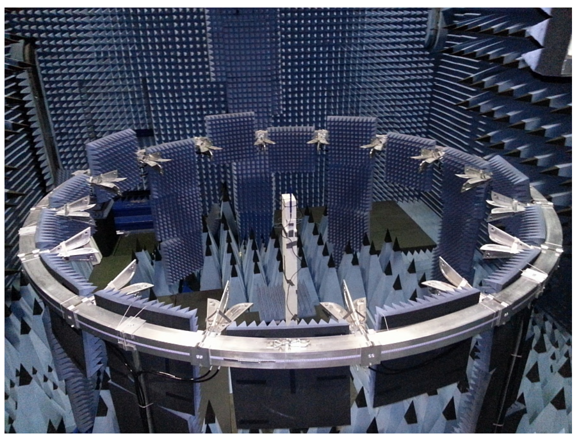

Figure 8: MIMO OTA testing range with 16 horns.

5 CONCLUSION

Three types of spherical arrays developed and used at AAU have been presented. These arrays have been instrumental in research into wireless channel characterization and future evaluation of MIMO mobile devices. Although the arrays require additional processing in order to obtain (or recreate) the direction of arrival, the main advantage is their capability of simultaneous coverage of the entire hemisphere, which would not be possible with standalone mechanically steered directional antennas.

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